Index Insurance induced moral hazards in fisheries have ambiguous affects on conservation

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Fisheries are vulnerable to environmental shocks that impact stock health and fisher income. Index insurance is a promising financial tool to protect fishers from environmental risk. However, insurance will change fisher behavior through moral hazards. We provide the first theoretical application of index insurance on fisher behavior change to predict if index insurance will incentivize overfishing or conservation of the stock. The direction of change depends on the risk characteristics of the inputs called risk effects. We find that index insurance will raise (lower) individual fisher effort when effort is risk increasing (decreasing). These results hold when a fishery is a common pool resource, but the welfare effects depend on the state of the fishery. Overfished stocks will gain from reductions in effort while undercapacity fisheries will gain from increased production. The direction of harvest change become ambiguous when accounting for interaction between multiple inputs. Simulating from parameters estimated from four Norwegian fisheries shows index inusrance could increase harvest as high as 15% or decrease harvest by 6%. Before widespread adoption, careful consideration must be given to how insurance will incentivize or disincentivize overfishing.

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1 Introduction

Fisheries are vulnerable to stochastic weather shocks. Environmental fluctuations directly impact fishers of all scales from large industrial vessels to small scale subsistence fishers. Fishing is a vital economic engine to coastal communities and is the primary source of protein for millions of people (Sumaila *et al.* 2012; Teh and Sumaila 2013; FAO 2020). Supporting these communities requires protection from enormous degrees of environmental risk.

Environmental variability in factors such as sea surface temperature or wind speeds impact fishery biological and economic productivity. Marine heatwaves increase animal thermal stress diminishing reproductive ability (Barbeaux *et al.* 2020), stunting growth (Pandori and Sorte 2019), pushing species outside their usual habitats (Cavole *et al.* 2016), and may directly increase mortality (Smith *et al.* 2023). Expanding fish habitat ranges increase costs when moving beyond the fishing grounds of established ports (Rogers *et al.* 2019). The variability from marine heatwaves alone impacts 77% of species within economic exclusion zones and reduce maximum catch potential by 6% (Cheung *et al.* 2021). Marine heatwaves are often accompanied by harmful algal blooms and diseases leading to additional fishery collapses (Oken *et al.* 2021).

The devastation of marine heatwaves was made clear in October 2022 when the Alaskan snow crab fishery was shut down after an assessment revealed an 87% decline in population from 2018 (Zacher *et al.* 2022). New evidence suggests that the marine heatwave increased caloric demands while tightening the snow crab range leading to a mass starvation event (Szuwalski *et al.* 2023). The fishery provided \$132 million from landings and \$174 million from processing in 2020, and the impacts from the closure will reverberate throughout the community (Garber-Yonts and Lee 2022). Recorded marine heatwaves have become more frequent (Holbrook *et al.* 2019) and climate change may continue to increase heatwave frequency as climate distributions become more variable (Frölicher *et al.* 2018).

Weather can also impact fisher harvesting efficiency beyond influencing the health of the underlying stock. Rolling seas and high wind speeds make it more difficult to harvest (Alvarez *et al.* 2006) in addition to raising the danger to crew and vessel (Heck *et al.* 2021). More intense storms threaten coastal infrastructure vital to fishing communities (Sainsbury *et al.* 2019).

Fishers actively avoid fishing in destructive weather at the expense of lost income (Pfeiffer 2020). All together, environmental shocks increase total income variability by changing harvest productivity or costs.

Individual choices by fishers and fishery management mitigate environmental risk. However, there is a lack of financial tools available to fishers to address income risk as a result of environmental fluctuations (Sethi 2010; Kasperski and Holland 2013). In the United States, financial relief currently comes from government issued disaster payments to afflicted fishery communities (Upton 2013). Since 1990, the United States has issued nearly $2 billion dollars to fishing communities after a disaster was declared. Environmental disasters, such as hurricanes, marine heatwaves, and harmful algal blooms, were solely responsible for 56% of the payments and partially responsible for another 27%. This system may be ineffective as there is an average of 2 years between disaster impact and fund relief (Bellquist *et al.* 2021), and may inequitably distribute funds (Jardine *et al.* 2020). New financial tools need to be developed to alleviate financial and income risk for coastal communities (Wabnitz and Blasiak 2019; Sumaila *et al.* 2020).

Insurance may be an ideal financial tool for risk management in fisheries as it is scalable, protects against environmental shocks, and smooths income for fishers (Watson *et al.* 2023). Currently, insurance in fisheries is primarily used to protect assets such as vessel hulls or fishing gear (FAO 2022). Insurance coverage could be expanded to include income variability. Weather fluctuations impact fisher income and their livelihoods. An insurance product covering environmental risk could improve fisher welfare and promote community resilience (Maltby *et al.* 2023).

Policy makers have begun pushing for new fisheries insurance programs modeled after agricultural crop insurance programs (Murkowski 2022). Index insurance is one such product touted by practitioners as a prime candidate for fisheries productivity insurance (Watson *et al.* 2023). Index insurance gained traction in agriculture as an effective alternative to traditional crop insurance in developing countries because it had lower administrative cost, minimized moral hazards, and does not require claim verification (Collier *et al.* 2009; Carter *et al.* 2017). Whereas crop insurance requires an assessment of loss to an individual farm, index insurance uses an independent measure as the basis for issuing payouts to all policyholders. For example, a pilot program through the Caribbean Oceans and Aqauculture Sustainability Facility (COAST) uses index insurance to payout a set amount to fishers when indices of wave height, wind speed, and storm surge indicate a hurricane (Sainsbury *et al.* 2019). Triggers are the index values that initiate a payout. Contract design revolve around establishing suitable triggers to cover environmental loss. Interest is growing in expanding index insurance to cover other environmental shocks to more fisheries.

One crucial area that remains unaddressed is the potential influence of insurance on fishers behavior. Moral hazards are decisions by insured agents that they would not otherwise take if they were uninsured (Wu *et al.* 2020). Owning insurance contracts will change fisher harvesting decisions through moral hazards. An early fishery insurance program in Bristol Bay, Alaska suggested insurance would disincentivize exit from the fishery exacerbating overfishing concerns (Herrmann *et al.* 2004). However, the authors provided no empirical or theoretical justification. Fisheries are highly dynamic systems because of year to year variation in biological growth and reproduction stemming from environmental variables. Overfishing impacts are exacerbated through ecological dynamics as lower fish abundances carry over to the next year. With 35.6% of global fisheries overfished and 57.3% at maximum sustainable yield (FAO 2022), ensuring new index insurance programs do not push more fisheries toward overfishing is a crucial first assessment.

Currently, the assumption appears to be that index insurance would completely avoid any moral hazards in fisheries (Watson *et al.* 2023). Yet, there are two components to insurance moral hazard: "chasing the trigger" and "risk reduction". "Chasing the trigger" is the directed behavior of policyholders to increase the likelihood of a payout. For example, a fisher actively choosing to fish less to receive an indenmified harvest insurance payment. Index insurance completely eliminates this moral hazard through the independent and uninfluenced index (fishers cannot affect sea surface temperature). "Risk reduction" occurs through possessing an insurance contract that protects policyholders from risk. Policyholders may reoptimize their decisions once protected from risk. Index insurance remains susceptible to this element of moral hazard that could manifest in maladaptive behaviors. A simple example would be choosing to not wear a helmet while riding a bike because you have health insurance. All preliminary analyses of fisheries index insurance are missing rigorous assessment of moral hazards. Moral hazards could enable behavior changes that lead to conservation of fish stocks or spiral delicate systems towards destruction.

Agricultural economists have grappled with insurance moral hazards for decades. While identifying insurance effects on inputs is an excruciatingly difficult task (Biram *et al.* 2024), there are numerous ways insurance has changed farmer's decisions. Farmers use more water (Deryugina and Konar 2017) and acreage with insurance coverage (Goodwin *et al.* 2004; Cai 2016; Claassen *et al.* 2017). The direction chemical input use varies with some studies indicating increased fertilizer use (Horowitz and Lichtenberg 1993), while others indicate less fertilizer use (Babcock and Hennessy 1996; Smith and Goodwin 1996). Mishra *et al.* (2005) were the first to connect the external environmental benefit of insurance through reduced fertilizer use. Suggesting that moral ahzards could be good for the environemnt.

Index insurance increased agricultural capital investments in Kenyan maize, Burkina Faso cotton, and Mali cotton farmers (Elabed and Carter 2018; Sibiko and Qaim 2020; Stoeffler *et al.* 2022). Index insurance also encouraged farmers in India to plant higher yield, but riskier crops (Cole *et al.* (2017)). In all instances, farmers took on riskier positions with the protection offered by insurance. A clear demonstration of the "risk reduction" element in index insurance moral hazards.

Increased investments through insurance can also harm communities, particularly in common pool resources such as livestock grazing. Kenyan index insurance for livestock discentivized preemptively selling animals after negative shocks, leading to larger herds in aggregate (Janzen and Carter 2018). Though no empirical work has been done on the long term effects, two theoretical studies suggest insurance increases the stocking levels of grazing animals in pastures.

Higher stocking densities diminish the pastures long-term health reducing overall utility gains of insurance (Müller *et al.* 2011; Bulte and Haagsma 2021). Caution must be demonstrated when dealing with complex bio-economic systems, otherwise maladaptive outcomes can lead to greater harm (Müller *et al.* 2017). The race to fish mentality that leads to overexploitation is a defining characteristic of fisheries. If index insurance always leads to increased input use in common pool resources, then implementing index insurance in fisheries could lead to maladaptive outcomes.

This paper explores how fishers could change their behavior if offered viable index insurance contracts. We start in Section 2 with the canonical Gordon-Schaefer fisher production model to show that one to one applications of index insurance in fisheries will always decrease fish stocks leading to loss in abundance. If we adopt more flexible production models from agriculture the affects of index insurance becomes ambiguous, and may lead to healthier fish stocks. We parameterize a model to demonstrate the potential impacts of index insurance. However, the empirical setting uses multiple inputs. Therefore, we extend the theoretical model to account for multiple inputs in Section 3 to develop clearer insights with possible input interactions. Numerical results in Section 4 estimate potential biomass loss or recovery with an index insurance program. Implications for the suitability of fishery index insurance are discussed in Section 5. Fishery index insurance ultimately has ambiguous effects on conservation. Before widespread adoption, careful consideration must be given to how insurance will incentivize or disincentivize overfishing.

2 Index insurance with standard fishery models

The Gordon-Schaefer production model continues to be one of the most used models in fishery modelling and management (Memarzadeh *et al.* 2019). Its simplicity captures a wide range of fishery dynamics and is easily extendable to more complex models such as age-structured (Tahvonen *et al.* 2018). The model finds steady state bioeconomic equilibrium that balances fish growth with fish harvest. Management targets such as maximum sustainable and economic yield (MSY and MEY) are easily derived from Gordon-Schaefer. Other popular surplus production models such as the Fox and Pella-Tomlinson models, can reduce down to the Gordon-Schaefer model through parameter choices. Given its ubiquity, it would be prudent to start with the Gordon-Schaefer model to understand how index insurance impacts fisheries.

Gordon-Schaefer captures biomass dynamics important to fisheries through the steady state equilibrium biomass. Additionally, it allows us to focus on a class of fisheries where behavior is unconstrained. Thus we can isolate the effects of insurance more clearly.

The original model derives steady state biomass through a logistic growth function and a linear technology function as a function of effort. Substituting into the linear technology function creates a production function yielding steady state harvest. Environmental stochasticity can translate to fluctuations in the steady state biomass.

$$
\begin{aligned}
y &= qe\tilde{B}(e) \\
\tilde{B}(e) &\sim N(\hat{B}(e), \sigma_b^2)
\end{aligned}
\tag{1}
$$

Where q is a catchability coefficient, $\tilde{B}$ is the random steady state biomass with a mean at $\hat{B}$ and a variance σ_b^2, and aggregated effort e. We can break apart the random variable into a mean effect $(\hat{\beta})$ and variance component (ω).

$$
\begin{aligned}
\tilde{B}(e) &= \hat{B}(e) + \omega \\
\omega &\sim N(0, \sigma_b^2)
\end{aligned}
\tag{2}
$$

Adding Equation 2 back into Equation 1 leads to:

$$
y = qe(\hat{B}(e) + \omega) \tag{3}
$$

This formulation is often referred to as process error (**Merino2022?**). Randomness could originate from weather shocks impacting equilibrium biomass in the current period or measurement error surrounding a stock (Tilman *et al.* 2018). Distributing the production terms leads to $y = qe\hat{B}(e) + \omega qe$, which we can generalize to any mean production function $f(e)$ and any risk function $h(e)$.

$$
y = f(e)\hat{B}(e) + \omega h(e) \tag{4}
$$

In Gordon Schaefer, $f'(e) > 0$ and $h'(e) > 0$ because catchability $q > 0$. Steady state biomass is decreasing in effort as well, $\hat{B}'(e) < 0$. Fishers derive utility from profits, so we add a convex cost function to harvest and normalize price of harvest to 1.

$$
\pi = f(e)\hat{B}(e) + \omega h(e) - c(e) \tag{5}
$$

To most seamlessly integrate index insurance, we can break situations into a bad state of the world that occurs with probability p and a good state of the world that happens with probability $(1-p)$. We can use ω to create an index to indemnify payouts because it captures the randomness of fishers profits. In reality, the index would be a weather variable known to impact biomass such as sea surface temperature, and the trigger are critical thresholds that cause weather to deviate from equilibrium biomass. Here, all stochasticity is captured by ω. We can align the states of the world to a shock trigger $\bar{\omega}$ so that $p = P(\omega < \bar{\omega})$ and $1 - p = P(\omega > \bar{\omega})$.

Insurance then pays a constant amount γ in the bad state. Actuarilly fair insurance allows the premium paid in both states to be the probability of receiving a payout $p\gamma$. Additionally, if we set the trigger to $\bar{\omega} = 0$ to indicate any time weather negatively impacts production, we can then separate out profit into good and bad states as well with $\omega_g > 0$ and $\omega_b < 0$ entering into Equation 5. Fishers are risk averse with a concave utility function $u'(\pi_i(e_i), \gamma) > 0$ and $u''(\pi_i(e_i), \gamma) < 0$. Putting it all together, fishers will maximize expected utility across good and bad states by selecting effort with a set insurance contract.

$$F \equiv \max_e \mathbb{E}[u] = pu(\pi_b + (1-p)\gamma) + (1-p)u(\pi_g - p\gamma) \tag{6}$$

The first order condition that solves Equation 6 is then:

$$\frac{\partial F}{\partial e} = pu'(\pi_b + (1-p)\gamma)\frac{\partial \pi_b}{\partial e} + (1-p)u'(\pi_g - p\gamma)\frac{\partial \pi_g}{\partial e} = 0 \tag{7}$$

For notional ease, the inputs of the profit function are dropped, but as shown in Equation 5 profit in both states (π_b=bad, π_g=good) remains a function of effort, equilibrium biomass, and weather shocks.

To find the impact of insurance on optimal effort we can apply Cramer's Rule to the first order conditions.

$$\frac{\partial e^*}{\partial \gamma} = -\frac{\frac{\partial F}{\partial e \partial \gamma}}{\frac{\partial^2 F}{\partial e^2}}$$

By definition of a maximization problem, $\frac{\partial^2 F}{\partial e^2}$ is negative so we can focus solely on the numerator to sign the impact of insurance on optimal individual effort. Then we'll use the change in individual effort to understand the implications on conservation.

Proposition 2.1. *Gordon-Schaefer production models will always lead to increases in optimal effort with feasible index insurance contracts.*

Proof. Differentiate equation Equation 7 with respect to insurance.

$$\frac{\partial F}{\partial e \partial \gamma} = (1-p)u''(\pi_g - p\gamma)\frac{\partial \pi_g}{\partial e}(-p) + pu''(\pi_b + (1-p)\gamma)\frac{\partial \pi_b}{\partial e}(1-p) \tag{8}$$

Suppose insurance fully covers the loss between states, then utility in the good state and bad state are equal to each other so that we can factor out like terms in Equation 8.

$$\frac{\partial F}{\partial e \partial \gamma} = (1-p)pu''(\cdot)[\frac{\partial \pi_b}{\partial e} - \frac{\partial \pi_g}{\partial e}] \tag{9}$$

The first term outside the brackets is negative by the definition of concave utility. Marginal profits across states share the same mean productions and costs as effort decisions must be made before the realization of the states. Subbing those terms in to Equation 9 demonstrates how they cancel out allowing us to sign the interior brackets.

$$\begin{aligned}\frac{\partial \pi_b}{\partial e} - \frac{\partial \pi_g}{\partial e} &= \omega_b h_e'(e) + \cancel{f_e'(e)\hat{B}_e(e)} + \cancel{\frac{\partial \hat{B}}{\partial e} f(e_)} - \cancel{c_e'(e)} \\ &- \omega_g h_e'(e) - \cancel{f_e'(e)\hat{B}_e(e)} - \cancel{\frac{\partial \hat{B}}{\partial e} f(e)} + \cancel{c_e'(e)} \\ &= \omega_b h'(e) - \omega_g h'(e)\end{aligned} \tag{10}$$

The marginal risk function is positive in Gordon-Schaefer so that $h'(e) > 0$. With $\omega_b < 0$ and $\omega_g > 0$, then Equation 10 is negative.

$$\frac{\partial \pi_b}{\partial e} - \frac{\partial \pi_g}{\partial e} = \overbrace{\omega_b h'(e) - \omega_g h'(e)}^{-}$$

Now can completely sign Equation 9 by subbing in the bracket sign to show that effort will always increase.

□

Proposition 2.1 solidifies the direction insurance impacts on optimal effort decisions. In turn this will lead to destructive conservation outcomes.

Proposition 2.2. *Index insurance always lowers steady state biomass in a Gordon-Schaefer model.*

Proof. Godron-Schaefer uses a logistic growth function so that mean equilibrium biomass always decreasing in effort, $\frac{\partial \hat{B}(e)}{\partial e} < 0$. By Proposition 2.1, effort will always increase with insurance. Therefore, equilibrium biomass will always decrease with insurance.

□

Contrary to initial hypotheses, index insurance will lead to maladapative outcomes in fisheries with standard models. Proposition 2.1 holds for more production models than just Gordon-Schaefer. Any production function where $h'(e) > 0$ including Cobb-Douglas, Pella-Tomlinson, and Fox models will lead to the same results. However, these models were not designed to tackle risk and risk aversion necessary for insurance in effective ways.

Agriculture also encountered a similar issue in the inception of crop insurance programs back in the early 1980s. Risk averse farmers choose inputs that deviated from expected values with Cobb-Douglas production functions. Researchers posited alternative flexible production functions to better capture the influence of risk on farmer decision making. Just and Pope (1978) specified the general class of functions that could adequately capture input risk effects that were both positive and negative. Inputs that lead to higher production variance are risk increasing with positive risk effects, and inputs that lowered the variance of production are risk decreasing with negative risk effects. Ramaswami (1993) and Mahul (2001) proved insurance would either increase or decrease the input use contingent on the risk effect qualities of a given input. Risk increasing inputs ($h'(x) > 0$) always lead to increases in input use with insurance, while risk decreasing inputs ($h'(x) < 0$) always lead to decreases in input use with insurance. Within this framework, Gordon-Schaefer and all other fishery production fisheries fall into the risk increasing category.

Fishers are highly sensitive to risk, especially income risk (Holland 2008; Sethi 2010). They mitigate risk through a variety of measures. Fishers will choose consistent, known fishing grounds over risking exploring unknown spots (Holland 2008). Fishers choose to fish less after storms and hurricanes when financial risk is alleviated by transitioning to catch share programs (Pfeiffer 2020; Pfeiffer *et al.* 2022). Perhaps they are making decisions surrounding risk beyond that which is modeled by Gordon-Schaefer. If we allow for risk decreasing inputs in fishery production, then the effects of insurance can flip to improve steady state biomass. The proof of Proposition 2.1 allows for risk decreasing inputs by switching $h'(e) < 0$ in Equation 10. The signs flip and insurance will lower effort leading to an increase in biomass by Proposition 2.2. Therefore we can preserve the prior results of agriculture in regards to the interaction of risk effects and insurance while introducing the dynamics of fisheries.

Allowing for flexible risk effects in the standard fishery models shows that the steady state impacts of insurance can either increase or decrease biomass. This leads to varying welfare impacts depending on the state of the fishery. In Figure 1, the first initial bieconomic equilibrium to the left demonstrates overexploitation with biomass below maximum sustainable yield. A decrease an effort from index insurance stimulates faster growth of the stock allowing for more harvest in the future. Therefore fishers will be more protected from shocks with insurance, benefit from more current harvest, and there will be a a healthier stock of fish. Alternatively, if inputs are risk increasing, then index insurance will shift production up, lowering harvest and biomass of the fish pushing the fishery further into overexploitation.

The second initial equilibrium to the right in Figure 1 is underexploited with biomass above maximum sustainable yield. The impact of index insurance on equilibrium biomass remains the same as when overexploited by Proposition 2.2, but the direction of harvest changes. Now, insurance will lower harvest for risk decreasing inputs and raise harvest for risk increasing inputs.

Figure 1 offers policymakers a powerful tool to assess the viability of using index insurance to protect fisheries from overharvesting and provide conservation benefits. Conservation of fish stocks through insurance hinges on the risk effects of production technology. If policymakers are solely interested in conservation, then only knowing the direction of the fishery risk effects is necessary. In that case, only fisheries with risk decreasing inputs should be targeted for

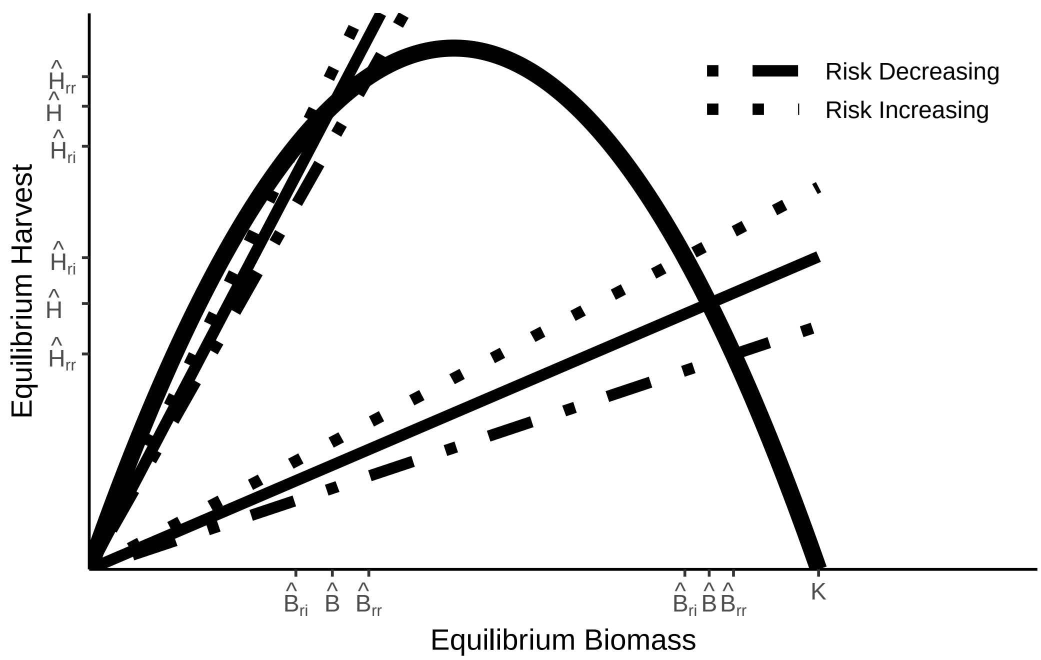

Figure 1: Equilibrium harvest and biomass levels change with index insurance depending on the risk effects of inputs. Deviations from initial harvest equilibriums (solid line) have different impacts at levels above and below maximum sustainable yield. Risk decreasing inputs (long dashes) will always lead to higher equilibrium biomass. Risk increasing inputs (short dashes) will always lead to lower equilibrium biomass.

index insurance policies. Index insurance could also be used to incentivize fishing in low capacity communities, much like how index insurance is used in developing countries to stimulate agriculture investment. Since most fisheries are overfished, it is unlikely that a policymaker would target fisheries with risk increasing inputs with insurance to expand capacity and place more pressure on the fish stock.

Risk effects remain an elusive concept in fisheries. It is unclear how to preemptively identify fishery risk effects. Specific inputs such as frost covers decrease the impact of weather on crops clearly. Other inputs have had more ambiguous results. Fertilizer in some contexts is risk increasing (Horowitz and Lichtenberg 1993) leading to crop burn, but other times is risk decreasing (Babcock and Hennessy 1996).

To date, only one study has quantified risk effects in a fishery setting. Asche *et al.* (2020) used data from four Norwegian fishing fleets to measure three input responses to risk. Each fishery possessed unique mixes of both risk increasing and decreasing inputs. For example, labor was found to be a risk decreasing input across all four groups, but only statistically significant in pelagic and coastal seiners. Capital was risk increasing for coastal seiners and trawlers, but flipped to risk decreasing for purse seiners and trawlers. Fuel had a lower, but statistically significant positive risk increasing measure for three of the four groups.

However, total output variance fluctuated widely. Coastal seiners had significant risk decreasing effects in labor, but also significant risk increasing effects in fuel. Overall output variance was insignificantly different than zero. So while individual inputs impacted risk, overall impacts were unclear. Before applying the risk parameters found by Asche *et al.* (2020), it is beneficial to build out a multiple input model to better understand how risk effects might behave in fisheries. Single variable aggregate effort measures are useful in surplus-production models, but do not reflect the complexity of fisher decisions. Index insurance may raise or lower individual inputs depending on their own unique risk effects, but the overall direction of harvest decisions cannot be determined. Little research has been done on multiple input insurance models. Ramaswami (1993) concluded that only total production variance drives total harvest changes, but does not elaborate on the individual response of inputs. The next section explores how multiple inputs interact with each other and insurance to provide a clearer picture of how index insurance will impact fisheries.

3 Insurance with multiple inputs

We can use the overarching framework from the previous section and expand it by adding multiple inputs. To simplify matters, we will normalize biomass to one as Asche *et al.* (2020) did not explicitly include biomass in their estimation model [1].

Some inputs have varying risk effects. Interaction between inputs risk effects could change overall impacts from insurance to aggregate harvest and biomass. Fishers can use a vector

[1] They used year fixed effects to account for biomass

of inputs X. Expected mean production ($f(X)$) and variance of outputs ($h(X)$) remains the same. We will use only two inputs, capital and labor, in our model. Total production thus equals:

$$
\begin{gathered}
y(k,l) = f(k,l) + \omega h(k,l) \\
\text{where } \omega \sim N(0,\sigma^2)
\end{gathered}
$$

As before, random shocks that could be weather or biological shocks is captured by ω. Mean production possess classic production concavity so that $f'(k,l) > 0$ and $f''(k,l) < 0$. Flexible risk effects imply that $h'(k,l) \lesseqqgtr 0$ so that risk increasing $h'(k,l) > 0$, risk decreasing ($h'(k,l) < 0$), and no risk effects $h'(k,l) = 0$. The original specification of Just and Pope make no assumption on the form of the second derivative of the risk effect function. To assist signing later on further justification is required. The marginal impact of adding an input to production variance should have diminishing effects, because it is impossible to completely eliminate risk or experience infinite risks. Therefore, when $h'(k,l) > 0 \rightarrow h''(k,l) < 0$, and when $h'(k,l) < 0 \rightarrow h''(k,l) > 0$. The cross partial of risk effects on production $\frac{\partial h}{\partial k \partial l}$ must also be flexible and depend on how inputs interact with each other. For example, if adding an input does not contribute to the marginal variance of another input then $\frac{\partial h}{\partial k \partial l} = 0$. Inputs interactions could be complementary in that adding a risk decreasing input further enhances the risk reducing properties of the other inputs, e.g. ($\frac{\partial h}{\partial k \partial l} > 0$). In other instances the inputs may interact counter actively in that adding more of a risk increasing input might reduce the effect of a risk decreasing input $\frac{\partial h}{\partial k \partial l} < 0$. In principle, when inputs share direction of risk effects, their cross partial ought to be complementary, and otherwise they will be counter productive.

Costs are convex, $c'(k,l) > 0$ and $c''(k,l) > 0$, in each input. Prices are constant and set at one so that production and costs together form random profits.

$$
\pi(k,l) = f(k,l) + \omega h(k,l) - c(k,l) \tag{11}
$$

We use the same insurance design from the previous section where payouts, γ, are triggered by $\omega < 0$, and we can partition profit into good states and bad states. Fishers now maximize expected utility by selecting both inputs, capital and labor.

$$
F \equiv \max_{k,l} \mathbb{E}[u] = pu(\pi_b(k,l) + (1-p)\gamma) + (1-p)u(\pi_g(k,l) - p\gamma)
$$

Taking the first order conditions yields:

$$
\begin{aligned}
\frac{\partial F}{\partial k} &= (1-p)u'(\pi_g - p\gamma)\frac{\partial \pi_g}{\partial k} + pu'(\pi_b + (1-p)\gamma)\frac{\partial \pi_b}{\partial k} = 0 \\
\frac{\partial F}{\partial l} &= (1-p)u'(\pi_g - p\gamma)\frac{\partial \pi_g}{\partial l} + pu'(\pi_b + (1-p)\gamma)\frac{\partial \pi_b}{\partial l} = 0
\end{aligned} \tag{12}
$$

Given the existence of the first order condition, we can use the implicit function theorem (IFT) to look at the impact of an exogenous variable change locally at the solution. In other words, using IFT will clarify how a change to the insurance parameter γ will lead to new allocations of captial and labor. We can differentiate Equation 12 with respect to γ by the chain rule. This yields:

$$\begin{pmatrix} \frac{\partial F}{\partial k \partial k} & \frac{\partial F}{\partial k \partial l} \\ \frac{\partial F}{\partial l \partial k} & \frac{\partial F}{\partial l \partial l} \end{pmatrix} \begin{pmatrix} \frac{\partial k^*}{\partial \gamma} \\ \frac{\partial l^*}{\partial \gamma} \end{pmatrix} = - \begin{pmatrix} \frac{\partial F}{\partial k \partial \gamma} \\ \frac{\partial F}{\partial l \partial \gamma} \end{pmatrix}$$

Inverting the Hessian matrix to the other side allows us to isolate the effects on the optimal allocations.

$$\begin{pmatrix} \frac{\partial k^*}{\partial \gamma} \\ \frac{\partial l^*}{\partial \gamma} \end{pmatrix} = - \begin{pmatrix} \frac{\partial F}{\partial k \partial k} & \frac{\partial F}{\partial k \partial l} \\ \frac{\partial F}{\partial l \partial k} & \frac{\partial F}{\partial l \partial l} \end{pmatrix}^{-1} \begin{pmatrix} \frac{\partial F}{\partial k \partial \gamma} \\ \frac{\partial F}{\partial l \partial \gamma} \end{pmatrix} \tag{13}$$

Crammer's rule allows us to solve this system of equations so long as the determinant of the system is not equal to 0. Luckily, the determinant is a 2x2 hessian of a concave maximization problem. By definition it is strictly positive. Applying Crammer's rule to Equation 13 gives us:

$$\begin{pmatrix} \frac{\partial k^*}{\partial \gamma} \\ \frac{\partial l^*}{\partial \gamma} \end{pmatrix} = \frac{-1}{Det} \begin{pmatrix} \frac{\partial F}{\partial l \partial l} & \frac{-\partial F}{\partial k \partial l} \\ \frac{-\partial F}{\partial l \partial k} & \frac{\partial F}{\partial k \partial k} \end{pmatrix} \begin{pmatrix} \frac{\partial F}{\partial k \partial \gamma} \\ \frac{\partial F}{\partial l \partial \gamma} \end{pmatrix}$$

Solving the systems yields:

$$\begin{aligned} \frac{\partial k}{\partial \gamma} &= \frac{-1}{Det} \left[\frac{\partial F}{\partial l \partial l} \frac{\partial F}{\partial k \partial \gamma} - \frac{\partial F}{\partial k \partial l} \frac{\partial F}{\partial l \partial \gamma} \right] \\ \frac{\partial l}{\partial \gamma} &= \frac{-1}{Det} \left[\frac{-\partial F}{\partial l \partial k} \frac{\partial F}{\partial k \partial \gamma} + \frac{\partial F}{\partial k \partial k} \frac{\partial F}{\partial l \partial \gamma} \right] \end{aligned} \tag{14}$$

Because the determinate will always be positive by the definition of the second order condition, we can focus on the interior of the brackets. If positive (negative), then insurance will lower (raise) use of that input. To sign Equation 14, we need to determine the partial derivatives. All six partials are included in the appendix. All the partials help define the impact of insurance on multiple input use.

Fishers must be risk averse, and inputs must contribute to risk management in some way. Otherwise, there will be no impact on insurance.

Proposition 3.1. *Risk neutral fishers will not change their input use with index insurance*

Proof. Risk neutrality implies that $u'(k,l) = 0$ and $u''(k,l) = 0$. Subbing $u''(k,l) = 0$ into both Equation 23 and Equation 24 forces them to both equal zero. Plugging zero for $\frac{\partial F}{\partial l \partial \gamma}$ and $\frac{\partial F}{\partial k \partial \gamma}$ into Equation 14 makes both elements also zero in the interior. Thus risk neutral fishers would not change input allocation with the addition of index insurance.

□

To help prove the remaining propositions, the following corollary will be valuable.

Corollary 3.1. *Marginal profit in the bad state of the world is greater (less) than marginal profit in the good state for risk decreasing (increasing) inputs. If inputs have zero risk effects, the marginal profits are equivalent in both states.*

The proof is included in the appendix.

Proposition 3.2. *Index insurance will not change the input allocations when all inputs possess no risk effects.*

Proof. The second part of Corollary 6.1 states that the marginal profits across states are equal. If the marginal profits across states are equal, then in Equation 23 and Equation 24 the weight between positive and negative utilities is also equal and cancel out leading to Equation 23 and Equation 24 both equaling zero. Plugging zeros into Equation 14 for the insurance partials leads to an interior zero and no change in input use.

□

Risk averse fishers will buy actuarially fair insurance. If the inputs possess risk effects then they will lead to changes in the input. Proposition 3.3 defines the change in multiple inputs simultaneously with insurance.

Proposition 3.3. *With multiple inputs, index insurance will raise (lower) use of risk increasing (decreasing) inputs in accordance to an inputs individual risk effects when the following sufficient condition is true:*

$\frac{\partial F}{\partial k \partial l} > 0$ *when both inputs share the same risk effects, and* $\frac{\partial F}{\partial k \partial l} < 0$ *when inputs have opposite risk effects.*

Otherwise, Index Insurance will have ambiguous effects on each input allocation.

Proof. Corollary 6.1 allows us to sign Equation 23 and Equation 24 for any risk effect on either input. Concave utility by definition leads to $u'' < 0$. For simplicity, we'll only focus on Equation 23, but all applies equally to Equation 24. Insurance payouts equalize profits between different states. If insurance completely covers all loss, then we can rewrite equation Equation 23 as

$$\frac{\partial F}{\partial k \partial \gamma} = \overbrace{\overbrace{(1-p)pu''(\cdot)}^{-}\,[\overbrace{\frac{\partial \pi_b}{\partial k} - \frac{\partial \pi_g}{\partial k}}^{-}]}^{+} \tag{15}$$

Corollary 6.1 allows us to sign the interior brackets of Equation 15. Risk increasing (decreasing) inputs make the interior negative (positive). Thus, when an input is risk increasing (decreasing), we can sign Equation 23 and Equation 24 as positive (negative). Equation 19 and Equation 20 will always be negative due to concave utility.

Suppose both inputs are risk increasing so Equation 23 and Equation 24 are positive. The only way for Equation 14 to be unambiguously positive is for Equation 21 and Equation 22 to be positive.

$$\frac{\partial k}{\partial \gamma} = \overbrace{\frac{-1}{Det}}^{-} \left[\overbrace{\overbrace{\frac{\partial F}{\partial l \partial l}}^{-} \overbrace{\frac{\partial F}{\partial k \partial \gamma}}^{+} - \overbrace{\frac{\partial F}{\partial k \partial l}}^{-} \overbrace{\frac{\partial F}{\partial l \partial \gamma}}^{+}}^{-} \right] > 0$$

$$\frac{\partial l}{\partial \gamma} = \overbrace{\frac{-1}{Det}}^{-} \left[\overbrace{\overbrace{\frac{-\partial F}{\partial l \partial k}}^{-} \overbrace{\frac{\partial F}{\partial k \partial \gamma}}^{+} + \overbrace{\frac{\partial F}{\partial k \partial k}}^{-} \overbrace{\frac{\partial F}{\partial l \partial \gamma}}^{+}}^{-} \right] > 0$$

Both risk increasing inputs will be raised with index insurance. The results hold for risk decreasing inputs as the overall signs flip. Risk decreasing inputs will be lowered with index insurance.

Now suppose inputs have mixed risk effects. For simplicity, capital will be risk increasing and labor will be risk decreasing. The results will hold for the opposite case. By Corollary 6.1, Equation 23 is positive, while Equation 24 is negative. Equation 14 will be unambiguously positive if Equation 21 and Equation 22 are negative.

$$\frac{\partial k}{\partial \gamma} = \overbrace{\frac{-1}{Det}}^{-} \left[\overbrace{\overbrace{\frac{\partial F}{\partial l \partial l}}^{-} \overbrace{\frac{\partial F}{\partial k \partial \gamma}}^{+} - \overbrace{\frac{\partial F}{\partial k \partial l}}^{+} \overbrace{\frac{\partial F}{\partial l \partial \gamma}}^{-}}^{-} \right] > 0$$

$$\frac{\partial l}{\partial \gamma} = \overbrace{\frac{-1}{Det}}^{-} \left[\overbrace{\overbrace{\frac{-\partial F}{\partial l \partial k}}^{+} \overbrace{\frac{\partial F}{\partial k \partial \gamma}}^{+} + \overbrace{\frac{\partial F}{\partial k \partial k}}^{-} \overbrace{\frac{\partial F}{\partial l \partial \gamma}}^{-}}^{+} \right] < 0$$

The risk increasing input will be raised with index insurance, while the risk decreasing input will be lowered.

$\square$

Proposition 3.3 shows that index insurance can have clear impacts even in complex settings with multiple inputs provided the sufficient condition holds. However, it is not clear ex-ante what the sign of the cross partial inputs of the first order condition should be. Equation 21 and Equation 22 themselves could be ambiguous. Rearranging Equation 21 and Equation 22 shows that the relative weight between the marginal profits of each input $\frac{\partial f}{\partial k}$ and the risk effects cross partial $\frac{\partial h}{\partial k \partial l}$ will determine the overall sign of the first order cross partials. Essentially, fishers change their inputs depending on whether a given input makes the other input more productive than the risk it adds. Dividing Equation 22 by $-\frac{u'}{u'}$ allows us to rearrange terms to show the tension between mean production and risk effects.

$$\begin{aligned}
-\frac{\partial F}{\partial k \partial l} &= (1-p)u' \frac{-u''}{u'} \frac{\partial \pi_g}{\partial k} \frac{\partial \pi_g}{\partial l} - (1-p)u' \frac{\partial \pi_g}{\partial k \partial l} \frac{u'}{u'} \\
&\quad + pu' \frac{\partial \pi_b}{\partial k} \frac{\partial \pi_b}{\partial l} \frac{-u''}{u'} - pu' \frac{\partial \pi_b}{\partial k \partial l} \frac{u'}{u'} \\
&= (1-p)u' [\frac{-u''}{u'}] \frac{\partial \pi_g}{\partial k} \frac{\partial \pi_g}{\partial l} + pu' [\frac{-u''}{u'}] \frac{\partial \pi_b}{\partial k} \frac{\partial \pi_b}{\partial l} \\
&\quad - (1-p)u' \frac{\partial \pi_g}{\partial k \partial l} - pu' \frac{\partial \pi_b}{\partial k \partial l}
\end{aligned} \tag{16}$$

The concavity of profit with positive risk aversion $\frac{-u''}{u'}$ lead line 3 in Equation 16 to be positive. The cross partials in line 4 paint a more complicated picture. Whether inputs enhance or reduce the risk effect qualities of each other influences the weight of line 4. When inputs share risk effects, they ought to increase the risk effects of each other so that $\frac{\partial h}{\partial k \partial l} > 0$. Therefore line 4 in Equation 16 becomes more negative as all terms are positive. It is relatively more likely that Equation 16 is negative when risk effects are shared.

When risk effects are mixed, with one input increasing and one input decreasing, the risk effects counteract each other $\frac{\partial h}{\partial k \partial l} < 0$. Line 4 in Equation 16 becomes relatively less negative. If the difference between the risk effects cross partial $\frac{\partial h}{\partial k \partial l}$ outweigh the mean production cross partial $\frac{\partial f}{\partial k \partial l}$ then line 4 becomes unambiguously becomes positive. Then $-\frac{\partial F}{\partial k \partial l} > 0$ and $-\frac{\partial F}{\partial l \partial k} > 0$. The relative changes with complimentary or counteractive risk effects matches the signs needed for the condition in Proposition 3.3 to hold.

Despite the seemingly rigid conditions, Proposition 3.3 is quite powerful. It states that the direction all inputs should change is based solely on the characteristics of their own risk effects. Other inputs may influence the magnitude of change, but the direction is unequivocal. It remains unclear how much overall harvest will change. Simulations show the total impact on harvest can vary substantially, and that the conditions to ensure unambiguous change can be met. Though when applied with real world estimates of risk effects, the conditions may not hold and the effects of index insurance may not follow simple rules.

4 Numerical Simulations

We use a simple numerical simulation to test the necessary conditions in Proposition 3.3 and to determine the magnitude of change in input use for Norwegian fisheries using the parameters found in Asche *et al.* (2020). First, we present the simulations from the two input case to gain additional insight into how index insurance changes multiple inputs. Fisher earn profit through harvest with a Just and Pope production function with mean biomass normalized to one, and convex cost function.

$$\pi(k, l) = \hat{B} k^{\alpha_k} l^{\alpha_l} + \omega k^{\beta_k} l^{\beta_l} - c_k k^2 - c_l l^2 \tag{17}$$

Random shocks (ω) are distributed normally with a mean of zero and a standard deviation of σ_w. Capital (k) and labor (l) have both mean production elasticities (α_k and α_l) and flexible risk elasticities (β_k and β_l). Fishers choose both capital and labor to maximize expected utility. We use a constant absolute risk aversion utility function.

Multiple index insurance policies are tested through changes in coverage and trigger levels. One scenario set constant payout amounts at 50% of pre-insurance profit and the other allows fishers to choose payouts. Trigger levels are set to engage at any below average weather, shocks of more than 75% loss, and catastrophic shocks that reduce biomass below 90%. All premiums are actuarilly fair. We vary fisher production parameters and risk aversion to create a comprehensive dataset of possible combinations. Risk effects vary between -0.7 and 0.7 with iterative increases of 0.1 ignoring situations of 0 risk effects. Fishers can posses low, medium, and high mean elasticity values $\alpha \in \{0.25, 0.5, 0.75\}$. Coefficient of constant absolute risk aversion ranges from 1 to 3. Within each scenario, a Monte Carlo simulation creates 1000 weather random weather shocks with three variants of standard deviation $\sigma_w \in \{0.33, 0.66, 1\}$.

4.1 Numerical simulation results

Increasing insurance incentivizes fishers to use more risk decreasing inputs and less risk increasing inputs (Figure 2). The conditions of Proposition 3.3 can be satisfied with CARA utility, a Just-Pope Production function, and normal values of mean and risk elasticities. Index insurance also increases utility shown by the green lines in Figure 2, but there exists an optimal amount of insurance coverage for fishers. The optimal values of insurance are generally lower when fishers use risk decreasing inputs. The inputs and insurance act as substitutes for each other both lowering the variance of income fishers experience.

Figure 2 shows that conditions of Proposition 3.3 can be satisfied, but it does not show the conservation outcomes of index insurance. Fishers use the new allocation of inputs to change their overall harvest and thus impact on the biomass of fish stocks. Harvest changes are influenced by the relative combination of risk effects, mean production elastiticies, and the amount of insurance. Fishers reduce harvest more aggressively with risk decreasing inputs when offered a set contract of 50% coverage of pre-insurance profits (Panel A) relative to their optimal choice (Panel B) (Figure 3). Allowing fishers to choose their insurance coverage leads them to increase harvest more with risk increasing inputs. This phenomenon relates back to Figure 2. A 50% coverage is an overinvestment in insurance for risk decreasing inputs and an underinvestment for risk increasing inputs.

Mixed risk effects reduce the overall impact on harvest. The more flexible risk parameter dominates the less flexible one in terms of which input reduces overall harvest shown in the top left and bottom right quadrants of both panels in Figure 3.

Increasing the mean elasticities exacerbates the discrepancies between allowing fishers to choose insurance payouts versus receiving a set amount. When the productivity of harvest (α) is higher, the tradeoff between reducing variance and catch changes. Though insurance protects against risk, lowering the use of risk reducing inputs looses more mean catch with higher production elasticities. Fishers reduce aggregate harvest less with risk reducing inputs when mean elasticities are high. The opposite is true for risk increasing inputs. Insurance protects against the variance of adding more inputs and fishers receive a greater mean catch.

4.2 Application to Real World Fisheries

Asche et al., (2020) aggregated by vessel type and not species, so there is no reasonable estimate for biomass. They accounted for biomass using fixed effects in their regression, but without additional information, our simulations normalize biomass to 1 and only focus on the relative change in inputs and aggregate harvest. The simulation model extends the two input case to include fuel (f).

$$\pi(k,l) = k^{\alpha_k} l^{\alpha_l} f^{\alpha_f} + \omega k^{\beta_k} l^{\beta_l} - c_k k^2 - c_l l^2 - c_f f^2 \tag{18}$$

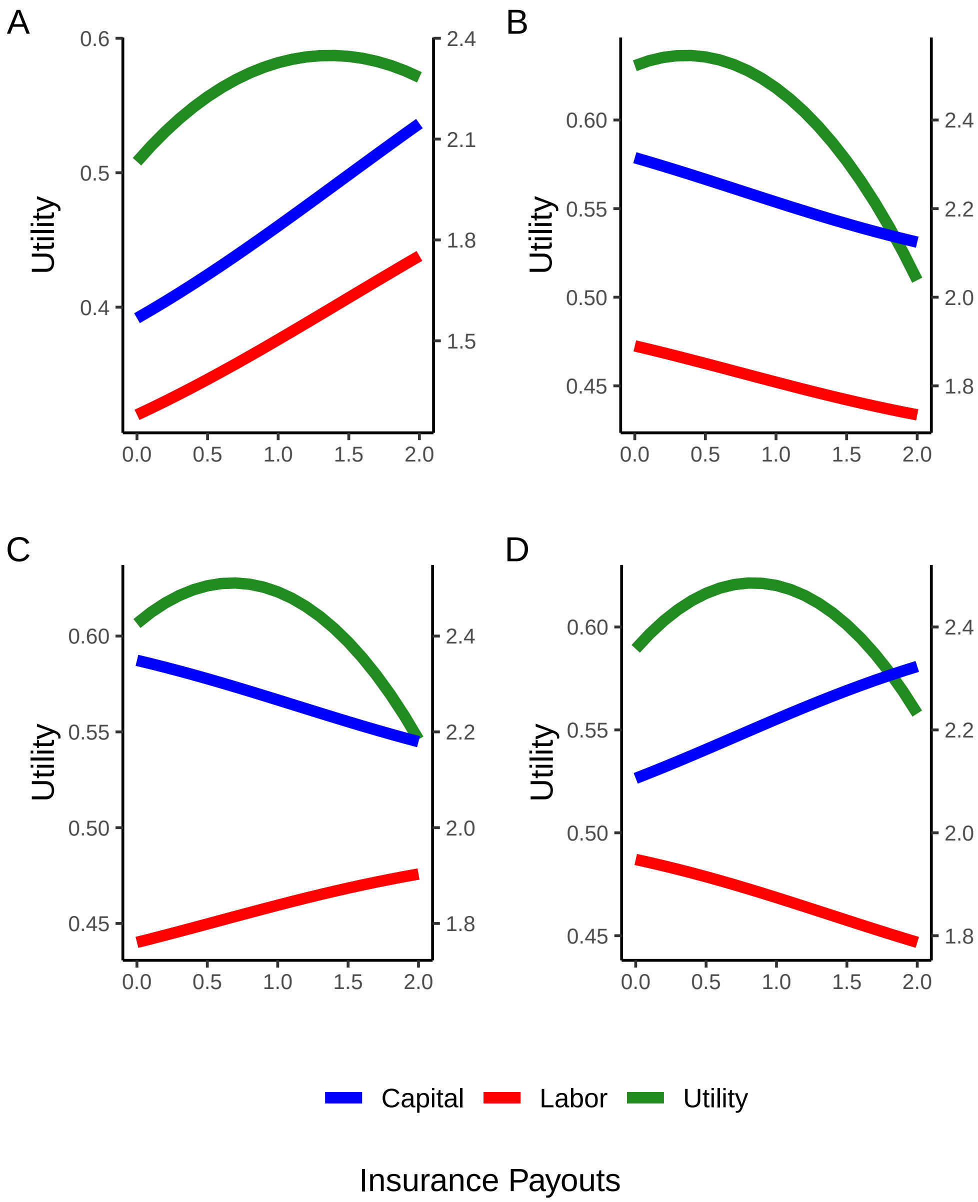

Figure 2: Fisher utility (green line) is concave in insurance payouts. Inputs change in accordance to their individual risk effects. The secondary y-axis shows input allocations for capital (blue line) and labor (red line). Panel A has both inputs with positive risk effects ($\beta = 0.5$). Panel B has both inputs with negative risk effects ($\beta = -0.5$). Panel C shows the effects when capital is a risk decreasing input ($\beta = -0.5$) while labor is risk increasing ($\beta = 0.5$). Panel D flips the risk effects of capital and labor.

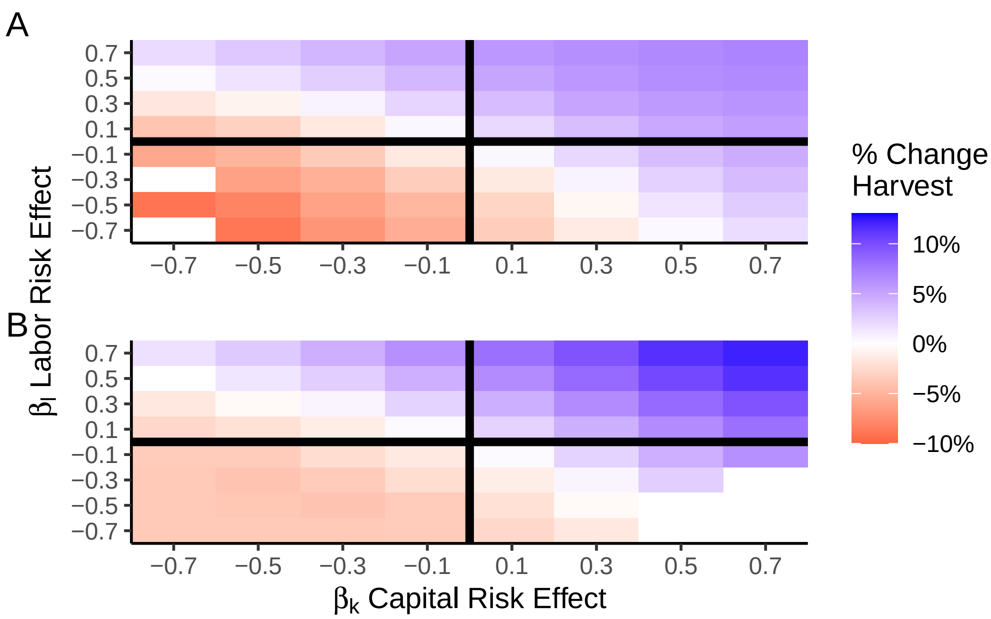

Figure 3: Percent Change in fishing harvest when fishers use index insurance with low mean elasticity values ($\alpha_{k,l} = 0.25$). In Panel A, Insurance payouts are a set variable. In Panel B, fishers choose insurance payouts. Red colors show overall decreases in harvest while blue colors show overall increases in harvest.

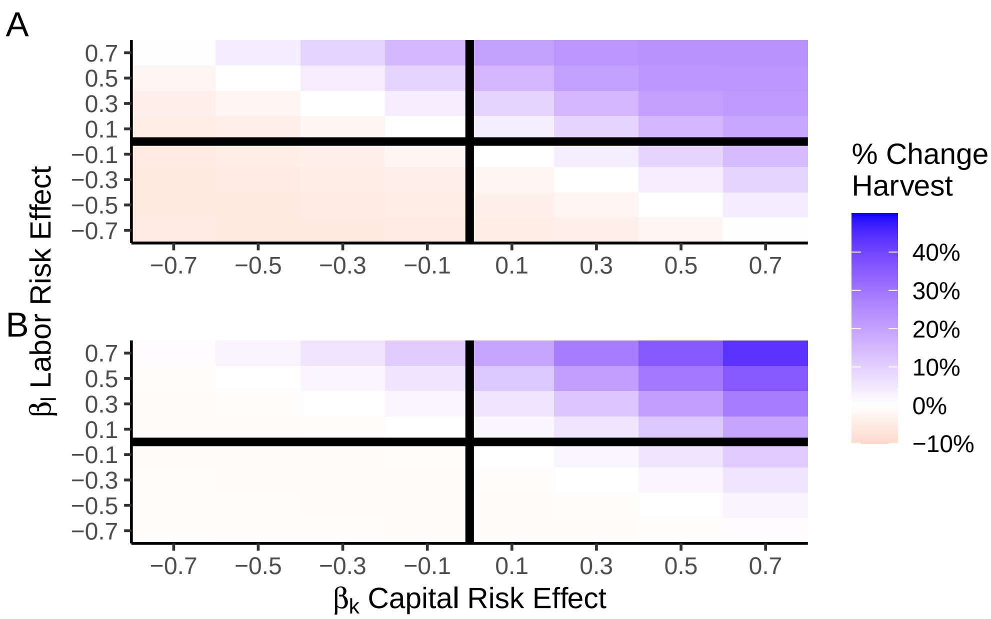

Figure 4: When fishers choose insurnace, they drastically increase (blue) harvest with risk increasing relative to no insurance harvest. Inputs share the same mean elasticity ($\alpha_{k,l} = 0.5$). Insurance payouts are a choice variable. Risk aversion is set to 1. Weather variance is 0.5

Table 1 shows the production and risk elasticities of the four vessel types used in the simulation. While not all elasticities were found to be statistically different from zero, we used their raw values because dropping only those variables that are significant in both matching parameters would have kept only a few valid combinations. All non-significant elasticities led to small changes as expected, but their interactions with other inputs could partially drive some of the observed outcomes.

Table 1: Production and Risk elasticities of Norwegian Fisheries

	α_k	α_l	α_f	β_k	β_l	β_f
Coastal Seiners	0.294	0.421	0.457	0.184	-0.432	0.119
Coastal Groundfish	0.463	0.421	0.355	0.965	-0.080	0.113
Purse Seiners	0.941	-0.108	0.605	-0.454	-0.231	0.160
Groundfish Trawlers	0.210	0.106	0.531	-2.788	-0.110	-0.024

Index insurance in Norwegian fisheries would have lead to changes in input use and overall harvest. Table 2 shows that index insurance would have lead to a maximum change of 15% in total harvest for the coastal groundfish fishery. This was primarily driven by large increases in capital (20.36%) and fuel (8.89%). All inputs had relatively similar mean production elasticities, but capital was strongly risk increasing with the highest positive risk elasticity. Labor was a risk decreasing input, but also rose with insurance. This is an example where the conditions of Proposition 3.3 do not hold. The large discrepancy in production risk elastiticites is probably a reason for this in addition to the interactions terms at play by adding a third input. The chosen insurance payout was also much higher than the other vessel types. This reflects the observation from Figure 2 that that fishers choose higher levels of insurance coverage as a means to substitute the additional risk they are taking with expanded production.

Purse seiners saw the largest reduction in overall harvest. Capital for purse seiners is the most productive input out of all fisheries and inputs. Because it is risk reducing, it dominates the slightly risk increasing fuel input to lead the entire fishery to reduce harvest by 6.3%. this shows another violation of Proposition 3.3. In the opposite direction this time. Labor allocations did not change. No labor was allocated in either optimal choice, because the production elasticity was negative. Insurance payouts were also higher than the other fisheries that saw reductions. The high productivity of capital and fuel were most likely driving this result because small reductions in these productive inputs needed larger compensations.

Coastal seiners are perhaps the most intriguing outcome, because all parameters were significant and shows the conditions for Proposition 3.3 can hold in the real world with multiple inputs. All input use changes followed their respective risk effects. Capital (0.44%) and fuel (0.11%) both increased, while labor (-1.01%) decreased. In aggregate, there was a small reduction in harvest (0.3%). While insurance lead to a change, it was rather small and would not have a large impact on the fishery. The counteractive effects of the risk effects may negate some of the desire to change production as insurance incentivizes both increases and decreases in harvest.

Inputs in the groundfish trawler industry were all risk reducing. Unsurprsingly, each input saw a reduction in use when index insurance was offered. Capital was exremely risk reducing and saw a 4.14% reduction in use, but was a relatively less productive input so overall harvest changed by only 1.4%. Inusrance payouts were selected to be low as seen in the two input simulations with risk decreasing inputs.

Table 2: Application of Index Insurance to risk effect parameters of Norwegian Fisheries

	Capital	Labor	Fuel	Harvest	Insurance Payout γ
Coastal Seiners	0.44%	-1.011%	0.11%	-0.3%	0.43
Coastal Groundfish	20.36%	6.578%	8.89%	15.4%	1.24
Purse Seiners	-4.39%	0.000%	-3.77%	-6.3%	0.81
Groundfish Trawlers	-4.14%	-0.979%	-0.69%	-1.4%	0.23

5 Discussion

Our paper is the first to investigate the interaction of risk effects and index insurance in a common pool resource. We emphasize a fishery setting due to burgeoning policy considerations and unique characteristics of fisheries that merit deeper elucidation. Index insurance has the potential to alleviate overfishing pressures in common pool fisheries, but it depends on the inputs risk effects. Risk effects control the direction and impact of index insurance on input use and harvest. Standard fishery models implicitly assume all inputs are risk increasing. Thus, applying index insurance in standard models will always lead to increases in fishing effort and reductions in stock biomass.

Risk effects need to be reconciled in a fisheries setting, particularly risk decreasing inputs. Crop covers and pesticide provide clear examples in agriculture, but what do risk decreasing inputs look like in fisheries? Asche *et al.* (2020) provide empirical evidence of the existence of risk decreasing inputs, but do not elaborate on why or how labor and capital directly decrease risk. Labor is perhaps the more intuitive risk decreasing input. Technical expertise of crew and captains can hedge against luck when fishing (Alvarez *et al.* 2006). Better trained crew can deploy gear in a safe and timely manner, increasing the likelihood of effective sets.

Capital is a more complex input, because it can be both risk increasing and decreasing. Capital investments in fisheries typically refer to vessel tonnage, engine power, and gear technology The spatiotemporal dimension of fishing decisions may explain how capital can potentially possess both risk effects. Fishers have to make decisions on where, when, and how long to fish that differ from the set grids of agriculture (Reimer *et al.* 2017). Capital offers protection from risk by allowing fishers to explore more fishing grounds, use more secure gear, and fish in more adverse weather conditions. When common pool resources incentivize the race to fish, having larger vessels may be a risk reducing input as the sooner a fisher can catch they assure their income at the expense of other fishers. Adding risk aversion to standard models of common pool fisheries suggests fishers should lower their capital use compared to risk neutral allocations (Mesterton-Gibbons 1993; Tilman *et al.* 2018). Yet, overcapitalization and overfishing are more often observed in the real world. Either fishers are never risk averse or the risk effects of capital are not as simple as the standard model suggests. When capital is allowed to be a risk decreasing, optimal allocations are much higher than risk neutral equilibrium suggesting fishers are making rational, risk averse decisions.

The transfer between inputs and insurance reflects the substitution between self-insurance and formal insurance (Quaas and Baumgärtner 2008). If index insurance is designed to reduce fishing capacity, efforts must be made to ensure that it does not take away from the self resiliency of fishers. Labor appears to be consistently risk reducing and acts as a form of self insurance. If index insurance incentivizes captains to hire less crew, the stock of fish may be preserved, but less employment may reverberate throughout the community. Fishing is often a primary employment opportunity in coastal communities. Lowering employment options may lead to increased poverty or concentrated wealth. The resiliency of the community would be compromised rather than enhanced. The same idea applies to capital. If fishers are overinvesting in capital to hedge against some form of risk, policymakers need to be sure the insurance is replacing maladaptive self insurance behavior.

The primary form of self insurance in fisheries is management. To this point our analysis explicitly modeled scenarios without the existence of management. Most fisheries are managed in some form. The interaction between management and insurance may be complementary or substitutes. For example, well managed fisheries that have responsive harvest control rules may not need insurance. The management system is already providing the necessary risk protection. Insurance demand and uptake may be low in these fisheries. Insurance may also complement management to provide the financial relief that management cannot offer. Managers often focus on the biological health of the fishery that can run at odds with fishers desire to enhance their income. Insurance can act as the financial relief and allow managers to pursue more active strategies to protect fish stocks without political resistance from lowered quotas. The interaction between insurance and management requires further investigation especially with the the numerous management strategies that exist in fisheries.

Design and access of insurance must also consider equity. The current federal disaster relief program is inequitable with bias towards large industrial vessels (Jardine *et al.* 2020). Replacing the program with an equally inequitable program would be foolhardy. Current US farm subsidies, including insurance premiums, are heavily skewed towards large agribusinesses (White and Hoppe 2012). Dimensions of access, procedural, representation, and distribution must all be built into the design of new fishery index insurance programs (Fisher *et al.* 2019). For example, small scale fishers may have income constraints that prevent them from buying the initial contract. Microfinance options connected to insurance have been used in agriculture to alleviate this burden to some success (Dougherty *et al.* 2021). Additionally, we must ensure that is not only the vessel owners who reap the benefits of insurance. Deckhands and crew are laid off during closures. If index insurance payouts are going through the entire fishery, the most vulnerable to closures must be protected as well. Contract stipulations could mandate that only cost expenses are covered by payouts thereby including lost wages to the crew. Agriculture contracts often are designed to directly cover expenses.

Our model only directly models behavior change through moral hazards. Index insurance could be designed to incentivize other forms of sustainable behavior change. We define three pathways insurance can change behavior: Moral hazards, Quid Pro Quo, and Collective Action. Moral hazards were proven in this paper to have ambiguous impacts controlled by the risk characteristics of fisher inputs.

Quid Pro Quo is the idea that insurance contracts could be designed with conservation measures built in. Fishers would be required to adopt sustainable practices in order to qualify for insurance. Quid Pro Quo is already used in agricultural insurance in the form of Good Farm Practices. Farmers must submit management plans to US Risk Management Agency that clearly outline their conservation practices in order to qualify for insurance. Working closely with management agencies, insurance companies could design contracts that require fishers to follow fishery specific management practices. For example, fishers may be incentivized to use more sustainable gear types, have an observer onboard, or reduce bycatch. Manager input is needed to tailor fishery best practices to insurance contracts. Further research would need to uncover the full impact of Quid Pro Quo, but an initial hypothesis would be the fishers will be willing to adopt sustainable practices so long as the marginal gain in utility from the insurance is greater or equal to the necessary sustainable changes. Otherwise fishers will not want to buy the contracts and the insurance has no binding stipulations to change the fishery.

Collective action ties insurance premiums to biological outcomes to leverage the political economy of the fishery. Insures could reduce premiums in fisheries that have robust management practices such as adaptive harvest control rules, stock assessments, or marine protected areas in the vicinity. Fishers could either pressure regulators to adopt these actions or form industry groups to undertake the required actions. Insurers would agree to this if triggers are connected to biological health so that negative shocks are less frequent and thus payouts occur less. Fishers gain from the insurance premium and the increases sustainability of harvest with rigorous management in place.

Ultimately, if index insurance is to be used in fisheries, it must be designed with clear objectives and intentions. Index insurance can meet objectives of income stability and risk reduction. There has been an implicit assumption by practitioners that index insurance will always lead to improved sustainability. Without considering the behavior change of fishers when adopting insurance, the outcomes may not be as expected. Index insurance will correct risk reducing overcapacity in specific fisheries providing boosts to the long term sustainability and conservation of fisheries.

6 Appendix

Partial Equations

$$\begin{aligned}\frac{\partial F}{\partial k \partial k} &= (1-p)u''(\pi_g - p\gamma)(\frac{\partial \pi_g}{\partial k})^2 + (1-p)u'(\pi_g - p\gamma)\frac{\partial^2 \pi_g}{\partial k \partial k} \\ &+ pu''(\pi_b + (1-p)\gamma)(\frac{\partial \pi_b}{\partial k})^2 + pu'(\pi_b + (1-p)\gamma)\frac{\partial^2 \pi_b}{\partial k \partial k}\end{aligned} \tag{19}$$

$$\begin{aligned}\frac{\partial F}{\partial l \partial l} &= (1-p)u''(\pi_g - p\gamma)(\frac{\partial \pi_g}{\partial l})^2 + (1-p)u'(\pi_g - p\gamma)\frac{\partial^2 \pi_g}{\partial l \partial l} \\ &+ pu''(\pi_b + (1-p)\gamma)(\frac{\partial \pi_b}{\partial l})^2 + pu'(\pi_b + (1-p)\gamma)\frac{\partial^2 \pi_b}{\partial l \partial l}\end{aligned} \tag{20}$$

$$\begin{aligned}\frac{\partial F}{\partial k \partial l} &= (1-p)u''(\pi_g - p\gamma)\frac{\partial \pi_g}{\partial k}\frac{\partial \pi_g}{\partial l} + (1-p)u'(\pi_g - p\gamma)\frac{\partial \pi_g}{\partial k \partial l} \\ &+ pu''(\pi_b + (1-p)\gamma)\frac{\partial \pi_b}{\partial k}\frac{\partial \pi_b}{\partial l} + pu'(\pi_b + (1-p)\gamma)\frac{\partial \pi_b}{\partial k \partial l}\end{aligned} \tag{21}$$

$$\begin{aligned}\frac{\partial F}{\partial l \partial k} &= (1-p)u''(\pi_g - p\gamma)\frac{\partial \pi_g}{\partial l}\frac{\partial \pi_g}{\partial k} + (1-p)u'(\pi_g - p\gamma)\frac{\partial \pi_g}{\partial l \partial k} \\ &+ pu''(\pi_b + (1-p)\gamma)\frac{\partial \pi_b}{\partial l}\frac{\partial \pi_b}{\partial k} + pu'(\pi_b + (1-p)\gamma)\frac{\partial \pi_b}{\partial l \partial k}\end{aligned} \tag{22}$$

$$\frac{\partial F}{\partial k \partial \gamma} = (1-p)u''(\pi_g - p\gamma)\frac{\partial \pi_g}{\partial k}(-p) + pu''(\pi_b + (1-p)\gamma)\frac{\partial \pi_b}{\partial k}(1-p) \tag{23}$$

$$\frac{\partial F}{\partial l \partial \gamma} = (1-p)u''(\pi_g - p\gamma)\frac{\partial \pi_g}{\partial l}(-p) + pu''(\pi_b + (1-p)\gamma)\frac{\partial \pi_b}{\partial l}(1-p) \tag{24}$$

Corollary 6.1. *Marginal profit in the bad state of the world is greater (less) than marginal profit in the good state for risk decreasing (increasing) inputs. If inputs have zero risk effects, the marginal profits are equivalent in both states.*

By the first order conditions, there exist optimal values k^* and l^* that must be chosen before the realization of the states of the world. Therefore $h(k^*, l^*)$, $f(k^*, l^*)$, and $c(k^*, l^*)$ are equal across states.

Marginal utility in both states of the world is controlled by risk effects and the sign of the random variable ω. Risk increasing inputs have $h'(k, l) > 0$ by definition. For either input k, l denoted by x this holds

$$\begin{aligned}\frac{\partial \pi_b}{\partial x} - \frac{\partial \pi_g}{\partial x} &= \omega_b h'_x(k,l) + \cancel{f'_x(k,l)} - \cancel{c'_x(k,l)} \\ &\quad - \omega_g h'_x(k,l) - \cancel{f'_x(k,l)} + \cancel{c'_x(k,l)} \\ &= \omega_b h'_x(k,l) - \omega_g h'_x(k,l)\end{aligned} \tag{25}$$

If an input is risk decreasing then $h'_x(k,l) < 0$ with $\omega_b < 0$ and $\omega_g > 0$. Then Equation 25 is positive and marginal profit in the bad state is greater than the marginal profit in the good state. Adding more of a risk reducing input reduces the negative impact in the bad state relative to the good state.

$$\frac{\partial \pi_b}{\partial x} - \frac{\partial \pi_g}{\partial x} = \overbrace{\omega_b h'_x(k,l) - \omega_g h'_x(k,l)}^{+}$$

Repeating the same thing for risk increasing inputs $h'_x(k,l) > 0$ shows that marginal profit in the bad state is less than marginal profit in the good state.

$$\frac{\partial \pi_b}{\partial x} - \frac{\partial \pi_g}{\partial x} = \overbrace{\omega_b h'_x(k,l) - \omega_g h'_x(k,l)}^{-}$$

If inputs have no risk effects then $h'(k,l) = 0$. Subbing into Equation 25 shows there is no difference in marginal profits with no risk effects.

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